Manufacturing and Technology Development Programs at First Solar

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ABSTRACT

During the past two years First Solar has concentrated heavily on process and product improvement in high volume manufacturing of high quality, low cost CdTe/CdS solar modules. Substantial improvements have been achieved in product stability, efficiency, and manufacturing costs. In 2002 First Solar began pilot line production of high quality modules for sale in the commercial marketplace. First Solar is currently carrying out its “Gen II Manufacturing Line” program that will increase module manufacturing capacity from its current value of 2 MW/yr to 25 MW/yr of 10% efficient modules by the end of 2004.

Critical technology development work underway will enable average production module efficiencies beyond 13% within 5 years. Current areas of focus for this longer term development work are: improved distributors for deposition of semiconductor films, improved methods to evaluate and improve module stability as efficiency is enhanced, and improved in-process metrology.

1. Current Manufacturing

During 2002 First Solar began commercial manufacture and sale of polycrystalline thin film CdTe PV modules. By the end of 2002 manufacturing throughput was at a rate of 2 MW/yr (800 7200 cm^2 modules/wk) and average total area module efficiency was 8% with yield of 70%. (See Fig. 1.) In addition, First Solar modules have been UL 1703 and IEC 61646 certified [1].

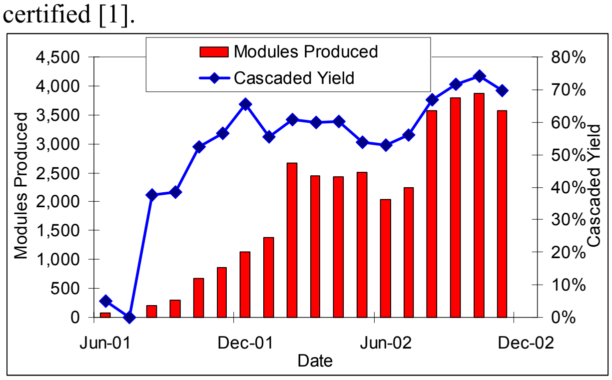

Figure 1. Modules produced and cascaded ieyeild.

First Solar has demonstrated champion modules of approximately 10% conversion efficiency, and these improvements are currently being introduced to the manufacturing line. Whole line module yields improved from <10% to greater than 70%, with expected yields in the high eighties by the time the Gen II line is operational.

Although there has been substantial progress in manufacturing volume, cost reduction, and efficiency improvement, much of the technical focus the last 2 years centered on stability improvement. First Solar routinely uses an internal stability test – a 56 day, 65 °C open circuit light soak – on a sample of production modules each month. The average efficiency degradation from initial value for modules made prior to the stability improvement activity was about -23%. Robust Engineering techniques utilizing Taguchi orthogonal array experiments were applied to this problem in late 2001. The experiments identified several process factors that could be adjusted to significantly improve module stability. The production line was brought back up with these improvements, resulting in average module degradation consistently better than -5% over the last year. First Solar is also aggressively engaged in a comprehensive outdoor testing plan. Thousands of modules have been deployed in various test fields throughout the country, many of which are independently operated and verified. The oldest of these arrays resides at NREL, with the latest report summarizing: “After seven years of operation, the loss in performance is comparable to that expected (1% per year) for commercially available crystalline silicon modules.”[2]

To capitalize on the progress made to date, First Solar is currently engaged in its “Gen II” program that will increase plant capacity to 25 MW/yr of stable, 10% total area efficiency modules. Gen II includes: 1) upgrading and replacing key pieces of equipment, 2) optimizing manufacturing processes though continuing Robust Engineering practices and 3) implementing demonstrated product performance enhancements that have been previously developed. This program of upgrades has been carefully and thoroughly planned using the proven Critical Chain program management methodology. At approximately 40% of the program completed, First Solar is ahead of schedule and expects the new Gen II line to be fully operational by November of 2004.

2. Distributors

CdTe and CdS films are deposited by vapor transport deposition (VTD) – a process that includes vaporization of powders of CdTe or CdS, their subsequent transport by a carrier gas and their distribution onto a glass superstrate [3]. Currently used CdTe and CdS distributors produce films of uniform thickness with good inherent material utilization efficiency, but there are spatial variations in grain size, crystallographic orientation and structural defect density across the width of the plate [4]. Advanced distributor designs are being developed that greatly reduce the cross-plate variation. Figure 2 displays how “roughness” – an internally defined variable that measures one manifestation of this variation – can be improved with an experimental distributor design. It is expected that improved distributors will be incorporated into the Gen II line. Additional improvements in efficiency are attributable to use of thinner CdS. As shown in Table 1, reducing CdS thickness has increased Jsc and Jmp by ~1.4 mA/cm^2 and total area module efficiency by ~0.5%.

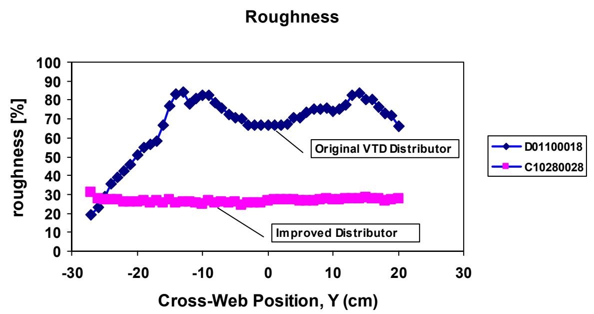

Figure 2. Roughness measured on plates deposited using "original" and "improved" distributor designs – both films are ~3.2 µm thick. Roughness is calculated from specular and scattered reflectance components.

Table 1. Production line module parameters from all modules produced between 10/1/02 and 2/10/03 – including test modules. Data are sorted by "target" CdS thickness; CdS thickness indicated is from on-line laser absorption measurement.

	"Thick CdS"	"Thin CdS"
CdS Thickness (Å)	3400	1740
Total Area Efficiency (%)	7.53	8.01
Jsc (mA/cm^2)	19.7	21.3
Jmp (mA/cm^2)	16.6	18.0
Voc/cell (mV)	751	748
Vmp/cell (mV)	530	523
FF (%)	59.3	59.1

3. Stability

Identification and minimization of mechanisms responsible for changes in cell performance is important for improving long-term reliability of CdTe thin film PV modules. Device performance under a variety of stressing conditions is investigated on the cell-scale (1.1 cm^2). Changes in material properties that are responsible for changes in IV-characteristics are induced by external stresses. Experiments include stressing of illuminated devices in a temperature range of 65°C - 115°C under open circuit, short circuit, resistive load, forward (≤ 38 mA/cm^2) and reverse (≤ -2V) bias conditions. In general, reverse bias seems to change the IV-characteristics most significantly, while open circuit and resistive load conditions induce less dramatic changes in relevant PV-parameters (See Figures. 3 and 4.) Changes in PV performance tend to saturate with time and temperature but elevated temperatures accelerate achievement of "stress saturation".

Effects summarized under the term "device degradation" are cumulative, so that more than one mechanism leading to device deterioration has to be considered. In other words, contributions from several mechanisms may work in parallel to produce separate material changes that lead to different degradation phenomena.

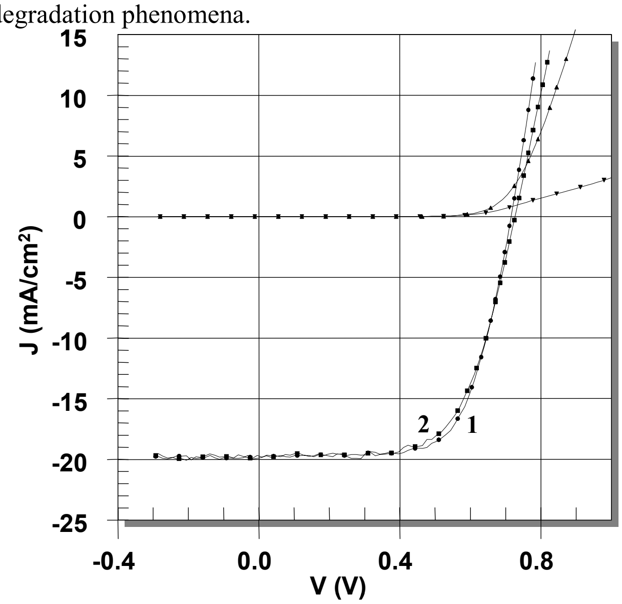

Figure 3. Dark and light IV-curves: 1) "pre-soak": 12h at Voc/light/90°C; 2) stress: 7d at Voc/light/90°C.

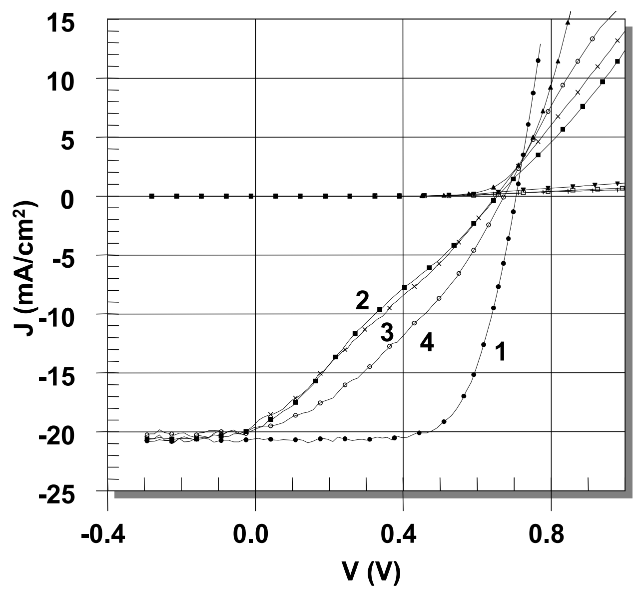

Figure 4. Dark and light IV-curves: 1) "pre-soak": 12h at Voc/light/90°C; 2) stress: for 7d at -2V/light/90°C; 3) after recovery for 1d at Voc/dark/25°C; and 4) after recovery for a total of 36d at Voc/dark/25°C.

As seen in Fig. 4, in some cases degraded devices partially recover upon being stored in the dark at room temperature with zero bias, suggesting that at least some of the degradation mechanisms are reversible. On the other hand, reverse biased devices do not return to their original performance and devices stressed in forward bias display less tendency to recovery. Thus it is possible that there are various mechanisms – reversible and irreversible – th- that work in parallel. While a detailed model has not been developed, a favored hypothesis is that material changes are driven by stress-induced changes in the local Fermi level. Equilibrium defect concentrations – within grains, at grain boundaries, and at interfaces –a- are determined by the local chemical potential and local Fermi level. Application of electrical bias or illumination changes the local Fermi level and therefore changes the local quasi-equilibrium defect concentrations. The local defect chemistry then tends to adjust toward the new local equilibrium, changing faster at higher temperature. As the internal distribution of defects changes, however, the relationship between the external electrical bias and internal Fermi level also changes leading to additional changes in the local equilibria. Thus material chemistry changes over time can be visualized as moving along a chemical pathway. Due to the changed local defect concentrations, restoring the external bias and illumination to their original values does not restore the local internal Fermi levels to their original values. Thus “irreversible” changes may be due to situations in which the material system cannot re-trace its chemical pathway. This model suggests than small changes in device chemistry may be reversible, but that excessive stress may induce irreversible changes.

Other irreversible changes may be attributed to chemical/material changes that are not associated with the Fermi level. For example chemical reactions may take place at the back contact or traces of adsorbed oxygen may become chemically active. Exploration of these mechanisms is the subject of ongoing studies.

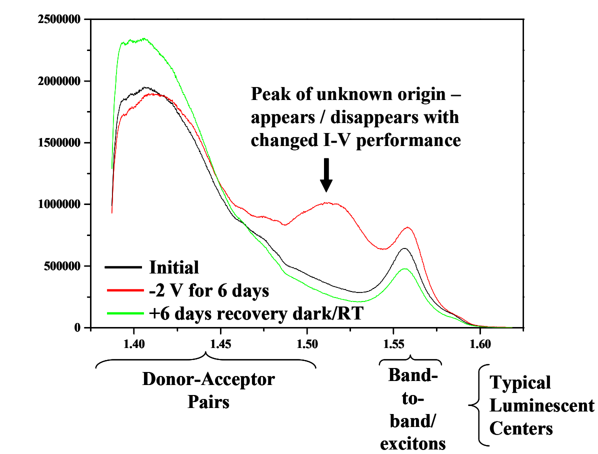

Figure 5. Representative photoluminescence data suggesting that certain metastable defects may be associated with reversible stress-induced changes in I-V behavior [5].

Photoluminescence (PL) measurements are used to detect native defects and impurity related states within the band gap of the CdTe absorber material, provided that recombination is radiative. A rough comparison of the PL spectra obtained for an unstressed and a sample stressed for 6 days under –2V (reverse) bias shows the development of a PL peak at around 1.5 eV - possibly due to a donor or donor-acceptor pair (DAP). As seen in Fig. 5, this PL peak disappears during device recovery under OC conditions in the dark, suggesting that in this case the defect chemistry is reversible. In addition, however, this PL peak is not observed for devices stressed under OC conditions (light) nor for devices that have achieved “stress saturation” at OC or reverse bias in the light, nor does this peak occur in all devices. In the case of “stress saturation” this “intermediate defect equilibrium” may have already been surmounted, so that the DAP can not be found.

4. In-Process Metrology

Spectrophotometery can be useful in thin-film photovoltaic manufacturing to monitor solar cell processing. Optical reflectance of glass/TCO/CdS/CdTe is measured in the wavelength range of 300-2500 nm using a Cary-500 spectrophotometer both from the glass side as well as from the CdTe side. Quantitative analysis is complicated because of multiple incoherent reflectances at interfaces and the reflection coefficients in their general forms must be used for evaluation. However, some parameters such as CdTe band gap can be easily obtained from the location of abrupt change in reflectance at the fundamental absorption edge due to abrupt change in the extinction coefficient of the film.

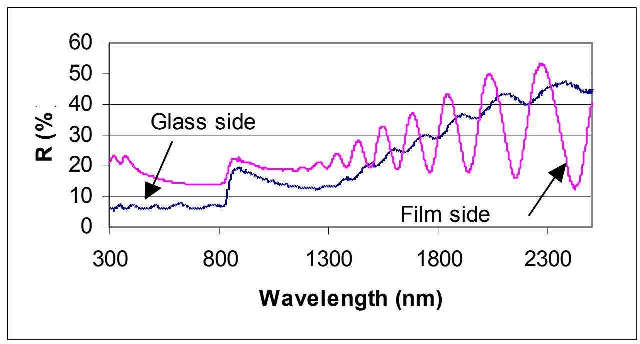

Figure 6. Spectral reflectance of the as-deposited glass/TCO/ CdS/CdTe structure from the glass side and from the film side.

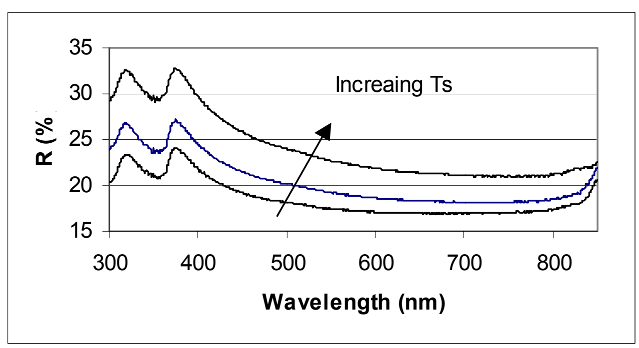

Fig. 7. Spectral reflectance of the $CdCl_2$-heat treated glass/TCO/CdS/CdTe structure from the film side for three different treatment temperatures.

A typical reflectance spectrum from as-deposited CdTe is shown in Fig. 6. The curve with high reflectance in the visible and strong interference fringes in the long wavelength range indicates reflectance from the film side. The second curve is for measurement from the glass side. A small interference effect from TCO and CdS films can be seen in the visible region from the glass side. This interference effect is not seen from CdTe side because no light is reflected back from the CdS/CdTe interface for light with energy higher than the CdTe band gap. A systematic change seems to take place in the overall reflectance as the samples are treated with Cl under different anneal temperatures.

Analysis of reflectivity spectra is being used to measure the systematic shift in CdTe band gap energy due to increased interdiffusion of CdS and CdTe that is observed with increasing Cl anneal temperature. Figure 7 shows reflectance profiles of three samples that were Cl annealed with slight changes in substrate temperature. The systematic increase in overall reflectance suggests increased mismatch in the optical coupling between air and film and/or systematic change in surface roughness. The two peaks at about 330 and 380 nm are the spin-orbit split-off valence band to conduction band transitions [6, 7].

X-ray diffraction (XRD) provides significant insight into the microstructure properties of the films and of changes that take place during Cl treatment. Studies to date, however, indicate that for devices of >10% efficiency there is not a good correlation between XRD and device PV properties such as Voc and FF. Device properties may therefore be dominated more by the electronic properties of the heterojunction than by bulk CdTe crystallographic properties.

Additional measurement techniques are being evaluated to achieve more robust and reliable in-line metrics of film characteristics during the fabrication progress.

5. Summary

First Solar has begun pilot line manufacturing of high quality, low-cost thin film CdTe modules with average total area efficiency of 8% and cascaded production line yield of >70%. Continued process optimization and incorporation of demonstrated product improvements will result in production of 25 MW/yr of stable, 10% efficient modules and >80% cascaded yield by the end of 2004. Technology Development programs in CdTe/CdS distributor development, materials chemistry and in-process metrology are providing improved semiconductor deposition capability, insight into improved device stability and capability for robust process control in support of programs that will further increase production line module efficiency to 13% within 5 years.

ACKNOWLEDGEMENTS

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